

OBSERVATIONAL EVIDENCE OF BACK-REACTION ON THE SOLAR SURFACE ASSOCIATED WITH CORONAL MAGNETIC RESTRUCTURING IN SOLAR ERUPTIONS

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ABSTRACT

Most models of solar eruptions assume that coronal field lines are anchored in the dense photosphere and thus the photospheric magnetic fields would not have rapid, irreversible changes associated with eruptions resulted from the coronal magnetic reconnection. Motivated by the recent work of Hudson, Fisher & Welsch (2008) on quantitatively evaluating the back reaction due to energy release from the coronal fields, in this Letter we synthesize our previous studies and present analysis of new events about flare-related changes of photospheric magnetic fields. For the 11 X-class flares where vector magnetograms are available, we always find an increase of transverse field at the polarity inversion line (PIL) although only 4 events had measurements with 1 minute temporal resolution. We also discuss 18 events with 1 minute cadence line-of-sight magnetogram observation, which all show prominent changes of magnetic flux contained in the flaring δ spot region. Except in one case, the observed limb-ward flux increases while disk-ward flux decreases rapidly and irreversibly after flares. This observational evidence provides support, either directly or indirectly, for the theory and prediction of Hudson, Fisher & Welsch that the photospheric magnetic fields must respond to coronal field restructuring and turn to a more horizontal state near the PIL after eruptions.

Subject headings: Sun: activity — Sun: flares — Sun: coronal mass ejections (CMEs) — Sun: magnetic topology — Sun: surface magnetism

1. INTRODUCTION

Solar eruptions, including flares, filament eruptions, and coronal mass ejections (CMEs) have been understood as the result of magnetic reconnection in the solar corona (e.g., Kopp & Pneuman 1976; Antiochos et al. 1999). Although surface magnetic field evolution (such as new flux emergence and shear motion) play important roles in building energy and triggering eruption, most models of flares and CMEs have the implication that photospheric magnetic fields do not have rapid, irreversible changes associated with the eruptions. The key reason behind this assumption is that the solar surface, where the coronal magnetic fields are anchored, has much higher density and gas pressure than the corona. Recently, we note the work by Hudson, Fisher & Welsch (2008, hereafter HFW08), who quantitatively assessed the back reaction on the solar surface and interior resulting from the coronal field evolution required to release energy, and made the prediction that after flares, the photospheric magnetic fields become more horizontal. Their analysis is based on the simple principle that any change of magnetic field energy must lead to a corresponding change in magnetic pressure. This is one of the very few models that specifically predict that flares can be accompanied by rapid and irreversible changes of photospheric magnetic fields. Over a decade ago, Melrose (1997) used the concept of reconnection between two current-carrying systems to provide explanation for the enhancement of magnetic shear at the flaring magnetic polarity inversion line (PIL), which is sometimes observed (see below). Perhaps this is in the same line as the tether-cutting model for sigmoids, which was elaborated by Moore et al. (2001) and involves a two-stage reconnection processes. At the eruption onset, the near-surface reconnection between the two sigmoid elbows produces a low-lying shorter loop across the PIL and a larger twisted flux rope connecting the two far ends of the sigmoid. The second stage reconnection occurs when the

large-scale loop cuts through the arcade fields causing erupting plasmoid to become CME and precipitation of electrons to form flare ribbons. If scrutinizing the magnetic topology close to the surface, one would find a permanent change of magnetic fields that conforms to the scenario of HFW08: the magnetic fields turn more horizontal near the flaring PIL due to the newly formed short loops there.

On the observational side, earlier studies were inconclusive on the flare-related changes of photospheric magnetic field topology. Wang (1992) and Wang et al. (1994) showed impulsive changes of vector fields after flares including some unexpected patterns such as increase of magnetic shear along the PIL, while mixed results were also reported (Ambastha et al. 1993; Hagyard et al. 1999; Chen et al. 1994, Li et al. 2000a, 2000b). It is not until recently that rapid and permanent changes of photospheric magnetic fields, mainly the line-of-sight component, are observed to be consistently appear in major flares and considered as indicative of flare energy release (Kosovichev & Zharkova 2001; Sudol & Harvey 2005). In particular, a number of papers of Big Bear Solar Observatory (BBSO)/New Jersey Institute of Technology group have been devoted to the finding of sudden unbalanced magnetic flux change (Spirock et al. 2002; Wang et al. 2002; Yurchyshyn et al. 2004; Wang et al. 2004a; Wang 2006) and a new phenomenon of sunspot white-light structure change (Wang et al. 2004b; Deng et al. 2005; Liu et al. 2005; Chen et al. 2006) associated with flares. By evaluating the mean relative motions between two magnetic polarities of five flaring δ spots, Wang (2006) revealed a sudden release of the overall magnetic shear and found a correspondence between converging/diverging motion and increase/decrease of magnetic gradient at the PIL, which suggests magnetic reconnection at or close to the photosphere. Liu et al. (2005) discussed outer penumbral decay and central penumbral darkening of δ spot seen in seven X-class flares, and proposed a reconnection pic-

TABLE 1
EVENTS WITH EVIDENCES OF ENHANCEMENT OF TRANSVERSE MAGNETIC FIELD (B_t) AT THE PIL

Event Date	GOES Level	Data Source	Data Cadence	Main Findings	References
(1) 1990 Aug 27	X3.0	BBSO	10 min	magnetic shear increase	1
(2) 1991 Mar 22	X9.0	BBSO	10 min	magnetic shear increase	2
(3) 1991 Jun 9	X10.0	BBSO/HSO	5 hr	magnetic shear increase	2
(4) 2000 Jul 14	X5.7	HSO	3 hr	B_t and electric current increase	3
(5) 2001 Aug 25	X5.3	BBSO	1 min	B_t and magnetic shear increase	4
(6) 2001 Oct 19	X1.6	BBSO	1 min	B_t and magnetic shear increase	4
(7) 2002 Jul 26	M8.7	BBSO	1 min	B_t increase	5
(8) 2003 Oct 29	X10	MSFC	3 hr	B_t and magnetic shear increase	6
(9) 2005 Jan 15	X2.6	BBSO	1 min	B_t and inclination angle increase	7
(10) 2005 Sep 13	X1.5	BBSO	1 min	B_t increase	8
(11) 2006 Dec 13	X3.4	Hinode	8 hr	B_t and magnetic shear increase	9

NOTE. — References: (1) Wang 1992; (2) Wang et al. 1994; (3) Wang et al. 2005; (4) Wang et al. 2002; (5) Wang et al. 2004a; (6) Liu et al. 2005; (7) Li 2010; (8) Wang et al. 2007; (9) Jing et al. 2008

ture where the active region field collapses inward after flares as signified by HFW08.

Although studying the change of magnetic field has promise to advance the understanding of flare energy release process, it is notable that the long-accumulated observational evidence have not yet converged regarding how the observed changes of photospheric magnetic fields could be understood in the context of models of coronal magnetic field restructuring. The objective of this Letter is hence to examine the observations in a systematic fashion and compare them quantitatively with the prediction of HFW08. Meanwhile, several conflicting concepts in our earlier papers will be reconciled with new physical understanding. We anticipate that these will guide more efficient studies to analyze vector magnetograph data of *Helioseismology and Magnetic Investigation* (HMI) on board *Solar Dynamic Observatory* (SDO) in the near future.

2. OBSERVATIONS AND RESULTS

The most straightforward way to determine changes of vector fields associated with flares is to monitor the time sequence of vector magnetograms. In order to detect any rapid and subtle variation, however, magnetogram observations with high cadence (a few minutes), high resolution ($1''$), and high polarization accuracy are required, and it is understood that *HMI/SDO* will be able to provide unprecedented data with these characteristics. Yet in the past two decades there are some vector magnetograms available that can tackle this topic with certain limitations. In Table 1, we summarize studies of changes of vector fields in previous publications. The data source was mostly the vector magnetograph of BBSO, which typically covers a field of view of $\sim 300'' \times 300''$ with an often cadence for a complete set of Stokes images of 1 minute. It has been noted that (1) the change of the measured field structure is subject to seeing variation; and (2) the system utilizes one position in the Ca I 6103 Å spectrum line thus the measured magnetic fields are saturated in regions with strong field strength. Nevertheless, it is almost impossible that the seeing fluctuation reproduces an identical trend of flare-related changes in multiple events. For almost all the events, we concern ourselves with the magnetic fields at the PIL where the weak field approximation is usually acceptable. Other ground-based magnetographs used include the filtergraph-based systems of Huairou Solar Observing station (HSO) of Beijing Astronomical Observatory and the Marshal Space Flight Center (MSFC), which have lower data cadence and bear similar restrictions as BBSO. For the 2006 Decem-

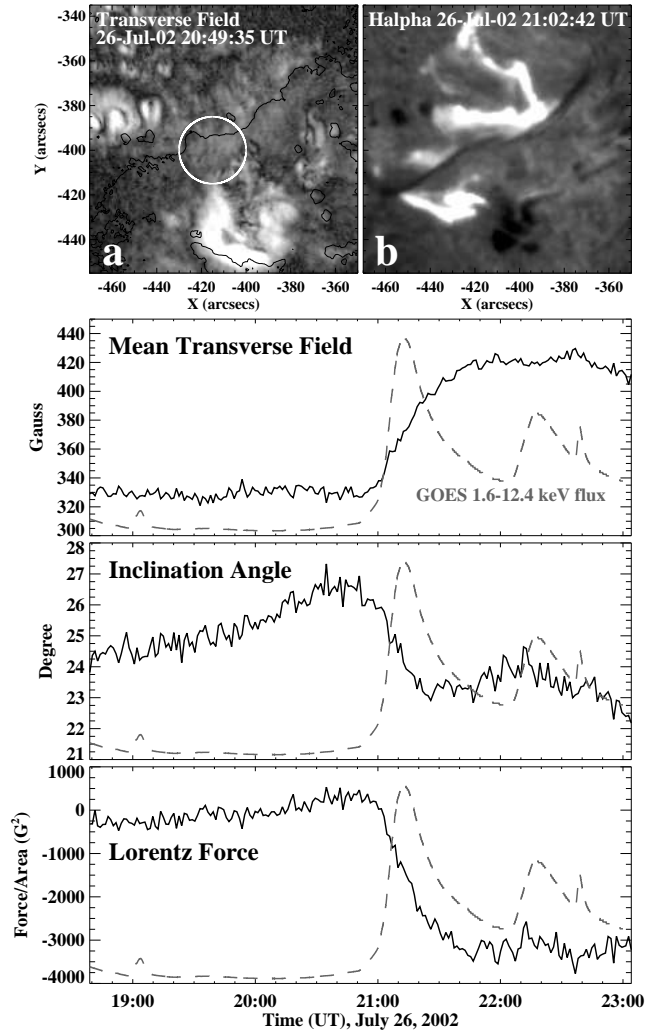


FIG. 1.— Time profiles of transverse field, inclination angle, and Lorentz force per unit area within a white circled region (in *a*) at the PIL (black line in *a*) for the 2002 July 26 M8.7 flare (see an $H\alpha$ image in *b*), calculated using BBSO vector magnetograms. In *GOES* 10 soft X-ray flux (dashed line), the flare started at 20:51 UT, peaked at 21:12 UT, and ended at 21:29 UT.

ber 13 event, vector magnetograms with highest polarization accuracy and resolution and taken under the seeing-free condition were obtained with the spectral polarimeter (SP) of the *Solar Optical Telescope* onboard *Hinode*, but the cadence of SP data is usually a few hours.

TABLE 2
EVENTS WITH EVIDENCES OF RAPID CHANGES OF ACTIVE REGION LINE-OF-SIGHT MAGNETIC FLUXES

Event	NOAA AR	Location (deg)	GOES Level	Limbward Flux (10^{20} Mx)	Diskward Flux (10^{20} Mx)	References
(1) 1991 Mar 22	06555	E20 S23	X9.0	+1.0	0	1
(2) 2001 Apr 2	09393	W64 N19	X20.0	+6.0	-1.5	1, 4
(3) 2001 Apr 6	09415	E30 S20	X5.6	+4.0	0.0	1
(4) 2001 Apr 9	09415	W04 S21	M8.0	+2.7	0	2
(5) 2001 Aug 25	09591	E34 S17	X5.3	+1.8	-0.8	1
(6) 2001 Sep 24	09632	E18 S18	X2.6	+10	-10	5
(7) 2001 Oct 19	09661	W29 N15	X1.6	+3.0	-0.4	1
(8) 2001 Oct 22	09672	E16 S18	X1.2	+11	-2	1
(9) 2001 Oct 25	09672	W26 S19	X1.3	-3	+5	5
(10) 2002 Jul 23	10039	E54 S12	X4.8	+0.15	-0.8	3
(11) 2003 Mar 18	10314	W53 S16	X1.5	+5.0	0	5
(12) 2003 Oct 19	10484	E54 N05	X1.1	+7	-2	1
(13) 2003 Oct 26	10484	N04 W41	X1.2	0	0	5
(14) 2003 Oct 28	10486	E04 S16	X17.2	+0.75	-0.4	2
(15) 2003 Oct 29	10486	W10 S17	X10.0	+0.65	-0.33	2
(16) 2004 Jul 16	10649	S10 E26	X3.6	+2.5	-10.0	5
(17) 2004 Nov 7	10696	N09 W08	X2.0	+5.0	-3.0	5
(18) 2005 Sep 13	10808	E17 S11	X1.5	+0.75	-1.2	2

NOTE. — References: (1) Wang et al. 2002; (2) Wang 2006; (3) Yurchyshyn et al. 2004; (4) Spirock et al. 2002; (5) This paper

With these cautions in mind, it is nonetheless obvious that all the results thus far point to the conclusion that transverse magnetic field strength increases at the PIL after major flares (namely, the fields there turn more horizontal), which provides direct and strong observational support for the theory of HFW08. Please note that (1) this kind of irreversible change of field strength at the PIL is not the magnetic transient that is caused by flare emissions and is hence co-spatial with flare ribbons or kernels (Qiu & Gary 2003; Patterson & Zirin 1981); and (2) our earlier studies were concentrated on the magnetic shear and it has been demonstrated that increases of magnetic shear and transverse field strength are interrelated (e.g. Wang et al. 2002). Following HFW08, we further quantify the change of Lorentz force per unit area in the vertical direction using the formula:

$$\delta f_z = (B_z \delta B_z - B_x \delta B_x - B_y \delta B_y) / 4\pi, \quad (1)$$

and present an example of our re-analysis of the vector field observations associated with the 2002 July 26 M8.7 flare in Figure 1. For the compact region at the flaring PIL (the circled area in Fig. 1a), the results unambiguously show the following. First, the mean transverse field strength increases ~ 90 G in about one hour ensuing from the rapid rising of the flare soft X-ray emission at 20:51 UT. This change-over time of transverse field strength between the pre- and post-flare states is longer than that of the most other events as well as that of the line-of-sight field reported in Sudol & Harvey (2005). Second, the inclination angle decreases $\sim 3^\circ$ accordingly, which indicates that magnetic field lines there turn to a more horizontal direction as predicted by HFW08. Third, the change of the Lorentz force per unit area is ~ -5000 G², integrated which over the analyzed area of $\sim 3.2 \times 10^{18}$ cm² yields a downward net Lorentz force in the order of 1.6×10^{22} dynes, comparable to what is expected by HFW08. Similar results have been found for other flares listed in Table 1.

Considering that vector magnetograms covering major flares with sufficient cadence and quality are rare and that reliable detection of rapid changes in the observed magnetic signals would ideally require stable observing conditions, we use the line-of-sight magnetograms ($\sim 2''$ pixel⁻¹) measured with the Michelson Doppler Imager (MDI) onboard the *Solar and*

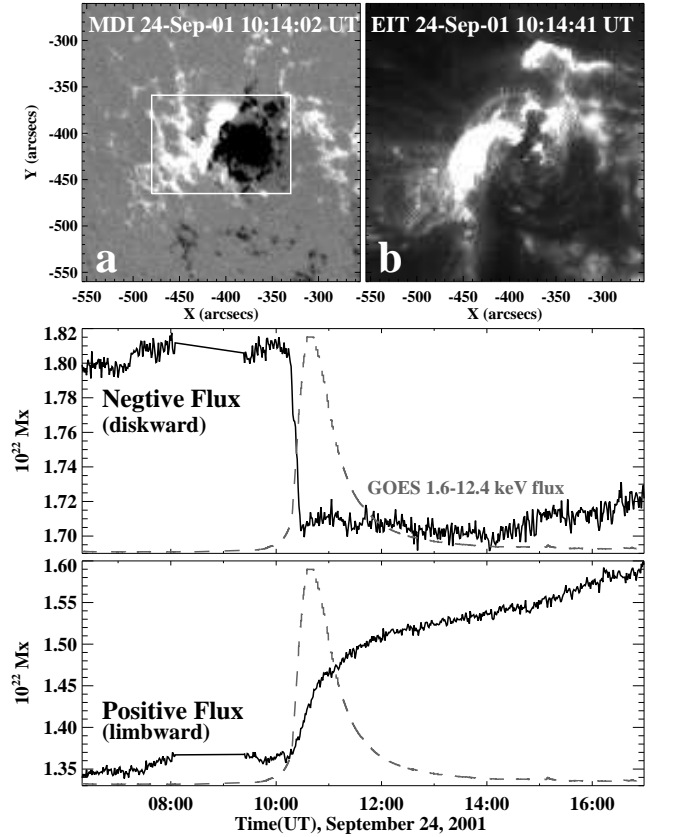


FIG. 2.— Time profiles of negative and positive MDI line-of-sight magnetic fields within a boxed region (in *a*) covering the entire δ spot for the 2001 September 24 X2.6 flare, seen in an EUV Imaging Telescope (EIT) image (*b*). In GOES 10 soft X-ray flux (dashed line), the flare started at 09:32 UT, peaked at 10:38 UT, and ended at 11:09 UT.

Heliospheric Observatory to add more events in the present study, taking advantage of its long-sequence and seeing-free data set. In retrospect, Cameron and Sammis (1999) was the first to introduce the concept of using line-of-sight magnetograms close to limbs as a probe for the orientation of transverse magnetic fields, which was elaborated further by Wang (2006). We surveyed all the X-class flares satisfying our event

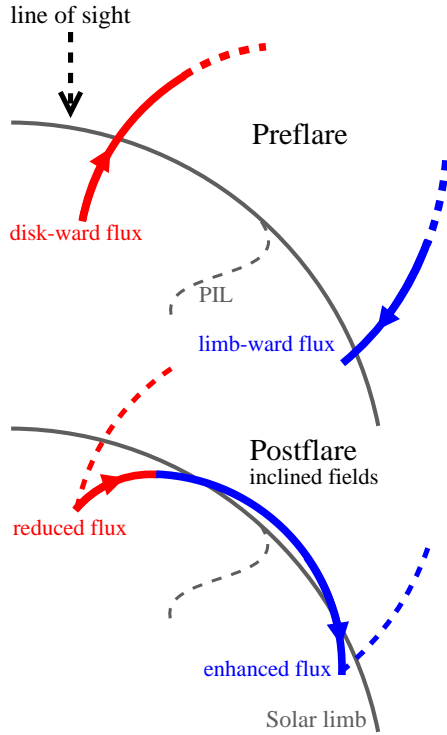


FIG. 3.— A conceptual cartoon to demonstrate the apparent changes of line-of-sight magnetic fields when the field lines turn more horizontal with respect to the solar surface. The limbward flux would increase while diskward flux would decrease.

selection criteria: (1) MDI magnetograms with 1 minute cadence are available spanning pre- and post-flare states for at least two hours each; (2) the source active region is within 65° from the disk center; and (3) Wang et al. (2000) concluded that there might exist two kinds of two-ribbon flares, one of which has small initial ribbon separation and occurs at the δ spot that possesses a well-defined PIL, and the other of which has wide initial separation of ribbons and is not associated with a clear and continuous PIL. We only chose the first kind of flares so that the flaring magnetic fields can be coherently determined and assessed. With these criteria, a total of 18 events are identified and are summarized in Table 2, a few of which are newly analyzed in this paper. Except for one case (2001 October 25 X1.3 flare), all events exhibit an increase of limbward flux and a decrease of diskward flux of active region magnetic fields after flares with an order of magnitude of 10^{20} Mx (no obvious changes can be detected for one of the two polarities in some flares). There is no doubt that all the changes are closely related with the flare occurrence and are substantially above the noise level with the largest percentage of change of $\sim 30\%$. As an instance, Figure 2 (lower panels) shows the line-of-sight magnetic field changes associated with the 2001 September 24 X2.6 flare (see Fig. 2b) at NOAA AR 09632, which are calculated for the boxed region of the entire δ spot (see Fig. 2a). It can be clearly seen that the limbward/diskward (positive/negative) fluxes increase/decrease for a similar amount of $\sim 10^{21}$ Mx right after the flare impulsive phase. The change-over time for positive and negative fluxes is ~ 40 and 10 minutes, respectively. As a matter of fact, these behaviors of line-of-sight fields also imply that the active region magnetic fields become more horizontal after flares, which was indicated by Wang (2006) based on limited sample events. Here we further demonstrate this

linkage in Figure 3. It shows that if the source active region is not located at the disk center, the measured apparent line-of-sight fields would undergo the aforementioned unbalanced changes due to projection effect, when the field lines collapse inward, that is, turn to a more horizontal state. Therefore, the theory of HFW08 is also indirectly substantiated by our results of line-of-sight field measurement.

It is worth mentioning that one can estimate the order of magnitude of the change of Lorentz force based on line-of-sight fields only using $\delta F_z = (B_z \delta \phi_z) / 4\pi$, where F_z is the integrated force and $\delta \phi_z$ is the integrated change of flux. With $B_z \sim 1000$ G and $\delta \phi_z \sim 10^{20}$ Mx, F_z is about 10^{22} dynes similar to what is derived before using vector data.

3. SUMMARY AND DISCUSSION

Synthesizing the research of flare-related rapid and irreversible changes in both vector and line-of-sight magnetic fields, we have revealed that photospheric fields apparently respond to the back reaction of coronal fields due to flare energy release, in a pattern that magnetic fields near the PIL become more horizontal, which strongly evidences the conjecture of HFW08. The change-over time lies between ~ 10 minutes to 1 hour, and all the changes are co-temporal with the flare initiation. These should provide insight into the upcoming *HMI* data analysis towards a more complete physical understanding of the impacts of flares on the solar atmosphere following coronal field restructuring. We discuss a few points related to observations and modeling work.

1. It is obviously reasonable that larger flares tend to produce more prominent field structure change (e.g., Chen et al. 2006). Using unprecedented *HMI* measurements, we anticipate finding a lower threshold of flare magnitude at which the magnetic field changes are still detectable.

2. A related aspect is that Hudson (2000) postulated that the energy conversion process during coronal transients would involve a magnetic implosion, which signifies that the flare ribbons and loops may contract initially before expansion. Although multi-wavelength signatures of such contraction have been observed recently (e.g., Liu & Wang 2009 and references therein), it is still unclear how to link it to the changing of field line orientation from more vertical to more horizontal configuration.

3. As our previous studies have shown, it is most likely that the strengthening of transverse fields near the PIL has a causal relationship to the enhancement of central penumbral structure of δ spots (e.g., Wang et al. 2004b; Liu et al. 2005). However, the penumbral decay in the outer boundary region is not reflected in the model of HFW08. We speculate that it is due to the peripheral field lines changing to more vertical state when the central region pressure is released after flares. That is to say, the surrounding fields might be subsequently pushed inwards to fill the void.

4. HFW08 introduced the concept of a “jerk” (i.e., downward push in the vertical direction due to the change of Lorentz force), which may account for the launch of seismic waves seen in some impulsive flares (Kosovichev & Zharkova 1998). This connection has other supporting evidence (e.g. Martínez-Oliveros & Donea 2009). A pertinent phenomenon is that a sunspot can have rapid flare-induced motion along the solar surface, which seems to be sufficiently driven by the changes of the horizontal components of Lorentz force (Anwar et al. 1994). Liu et al. (2010, in preparation) presented five new events in an effort to associate the kinetic energy of sunspot lateral motion with that of seismic waves, while

we must note that the detailed mechanism involved has never been researched before. In addition, although the events with seismic waves always have associated rapid changes of surface magnetic fields, it seems that this conclusion cannot be reversed as suggested by several cases under study. The new research area will shed more light on understanding the linkage between the sub-surface/surface magnetic activities and

coronal eruptions.

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